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A METHOD FOR REDUCING DATA FROM RADIOGRAPHS OF SHAPED-CHARGE JETS

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This report is a users' guide intended for those involved in reducing data from radiographs of shaped-charge jets. The procedure for setting-up and reading radiographs is listed step-by-step. A computer code listing and description of the calculations are included. Jet particle velocities, break-up time, kinetic energies, lengths, diameters, length-to-diameter ratios, masses, momentums, and jet virtual origin are all included in the code.

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I. INTRODUCTION

With measurements taken directly from flash radiographs of shaped-charge jets before and after breakup, quantitative information describing particulated jet characteristics can be derived. The measurements are used to calculate such properties as particle length, diameter, velocity, mass and break-up time. It is, however, a very tedious and time consuming operation to take the measurements by hand and subsequently perform the calculations at one's desk. To alleviate much of this work, a method using digitizing equipment and a computer program has been developed and is the subject of this report. This method has proven to be very useful, especially in projects involving many rounds and requiring short turn-around time for measurements and computations.[1,2] The equations used in the computations will be discussed in the next section. Appendices for film reading procedures and for the computer program operation are included.

II. COMPUTATIONS AND EQUATIONS

The program was designed to calculate as many quantities as possible with the data extracted from radiographs. This includes individual particlesas well as the whole jet measurements. Since this report is intended as a user's guide, the calculations will be described briefly. All computations are tabulated in the output with proper headings. A typical output is shown in Appendix E.

All radiographs contain slightly magnified images of the particles of a shaped-charge jet. The positions of the particles are likewise altered from their true positions relative to the base of the shaped-charge liner. This difference is taken into account by the magnification factor, M, which is determined by the ratio of the distance, a, from the face of the x-ray tube to the jet path, to the distance, b, from the tube face to the film, as depicted in Figure 1. Thus, $M = a/b$. This factor is used in determining particle lengths, diameters, and positions. To calculate lengths and diameters, the measurements taken from the particle images on film are simply multiplied by the magnification factor.

To calculate change in position the magnification factor is used in the determination of a particle's true position during a given flash. Two cases must be considered regarding the film location in

[1] *R. L. Jameson, and H. J. Blische, "A Study of a Light Anti-tank Weapon," report in preparation.*
[2] *D. Dorfman, and S. K. Golaski, "Electro Formed Shaped Charge Liner Evaluation," report in preparation. Martin Marietta Corp. Contract #DAAK 11-77-0088.*

the determination of position. Refer to Figure 1 for the locations of the terms involved. Note that on all films the distance, p, from the fiducial to the particle is positive below the fiducial and negative above.

Case I: Film numbers 1 and 2.

$$s = F - [(f-p)\ M\ ] ,$$

where s is the true position, F is the distance from the shaped-charge liner base to the x-ray tube focal level, f is the location of the y fiducial relative to the focal level, p is the point on the particle measured from f, and M is the magnification factor.

Case II: Film numbers 3 and 4

$$s = F + [(f+p)\ M\ ] .$$

Once the positions have been determined for all flashes, velocity is calculated by

$$v = \frac{s_b - s_a}{T_b - T_a} ,$$

where $s_b - s_a$ is the distance of jet travel between the earlier (a) and later (b) flashes, and $T_b - T_a$ is the change in time between the flashes.

Break-up time is determined by the equation developed by Simon.[3]

$$t_b = \frac{\sum_{i=1}^{n} \ell_i}{v_1 - v_n}$$

where ℓ_i is the individual particle length, v_1 is the velocity of the first particle and v_n is the velocity of the nth particle.

---

[3]*J. Simon, "The Effect of Explosive Detonation Characteristics on Shaped Charge Performance," BRL Memorandum Report 2414 (1974). (AD #B000337L).*

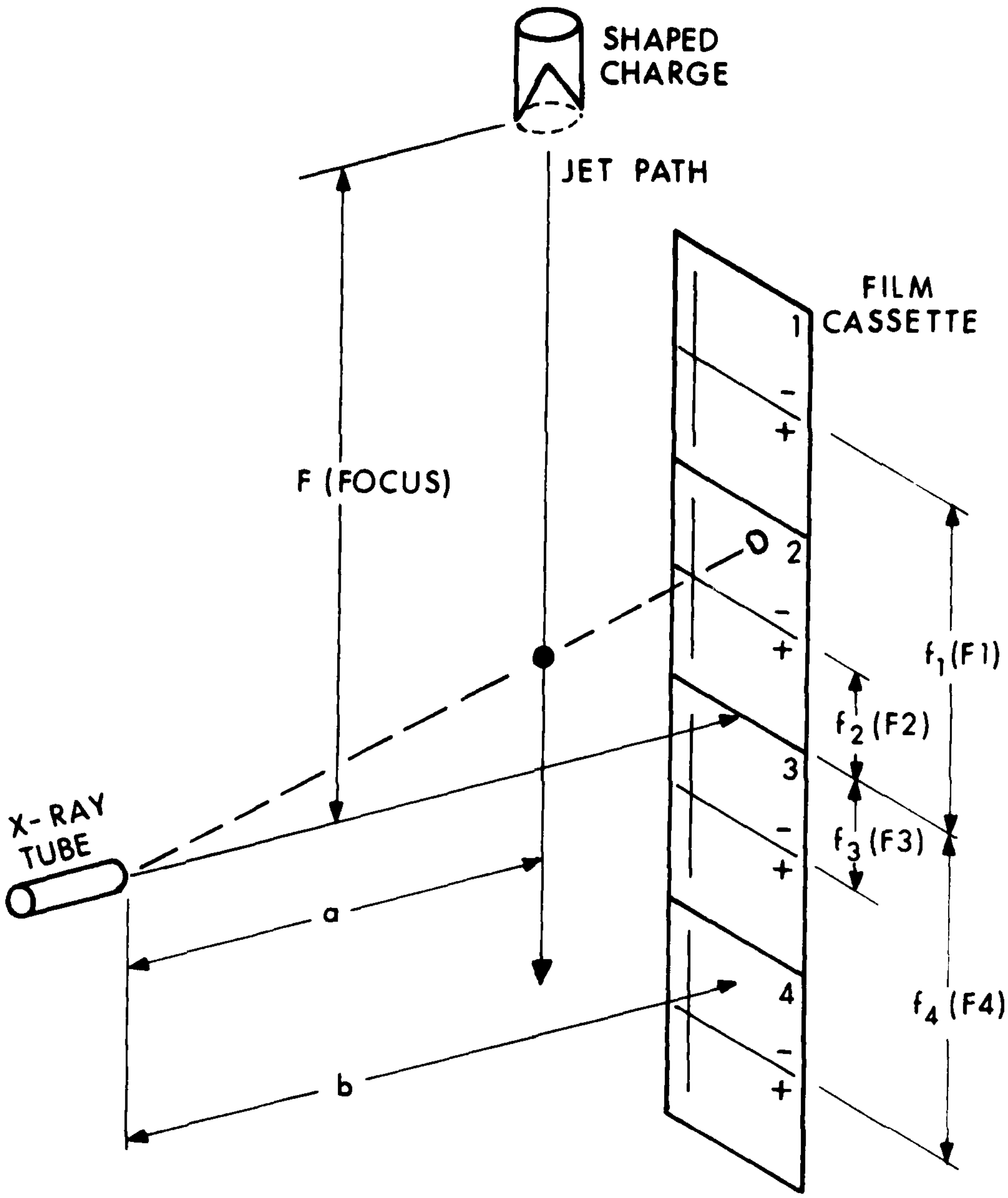

Figure 1. Typical Flash X-ray Set-Up Showing Relative Positions of the Apparatus

Mass calculations involve the equation for the volume of a truncated cone. As described in Appendix A, points located around the film image of a particle outline a pair of trapezoids. This is also shown in Figure 2. The program interprets the coordinates of the points as measurements for truncated cones and applies the equation for mass, m, where

$$m = \rho \, \frac{\pi}{3} \, [H_1(R_1^{\,2} + R_1R_2 + R_2^{\,2}) + H_2(R_2^{\,2} + R_2\,R_3 + R_3^{\,2})] \; .$$

Here, ρ is the density of the shaped-charge liner material, H_1 and H_2 are the heights of the truncated cones, and R_1, R_2 and R_3 are the radii.

Momentum (mv) and kinetic energy ($\frac{1}{2}\ mv^2$) are finally calculated using velocity and mass previously computed.

The virtual origin of the shaped-charge jet is found by fitting a least-squares line through the particle velocity/particle position data for each flash. Theoretically, the position of the virtual origin corresponds to a particle velocity of zero.[4]

Tabulations of the above mentioned quantities are performed and listed in the output as averages. However, for the purpose of trouble-shooting, and to gain insight into the accuracy of the average computed quantities, velocities between the flashes and masses for each flash are also listed.

---

[4] *R. DiPersio, J. Simon and A. B. Merendino, "Penetration of Shaped-Charge Jets Into Metallic Targets," BRL Report 1296 (1965). (AD #476717).*

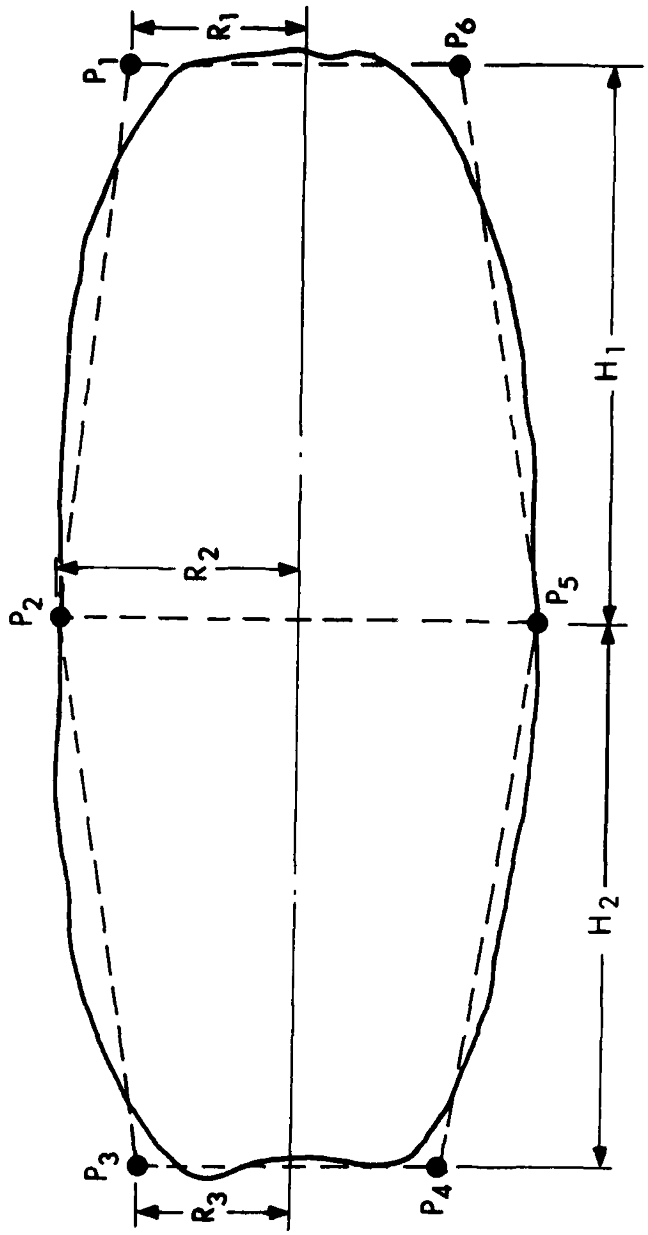

Figure 2. Particle Shape Approximation. Dashed lines **outline** two trapezoids that are interpreted as truncated cones in the program.

III. SUMMARY

As indicated earlier, this method quickly yields valuable information necessary for the evaluation of shaped charge designs. A large number of radiographs can be data reduced in a few days, whereas the same number would take months if reduced by hand. This has the advantage of giving the shaped charge investigator more flexibility by allowing more time to assess designs and make decisions.

For accuracy considerations, comparisons of some measurements were made with other findings, and an error estimate of one measurement was performed. Velocity, length, diameter and break-up time calculations for the round in Appendix E were compared to data of several similar rounds as reported by Majerus[5]. The quantities in Appendix E were found to be within the range of Majerus' data. There is a problem, however, with particle mass calculations. An error estimate for the mass of a selected particle revealed that the measurement could be incorrect by approximately 60%. Several factors are involved in this large error including magnification measurements, digitizing equipment accuracy, image clarity and coordinate point locations. Referring back to Figure 2, note that the group of points surrounding the particle does not represent a contour mapping of the particle shape but approximates two truncated cone geometries. This is where the largest part of the error occurs. Ideally, a much larger number of digitized points would give a better approximation of shape, but the equipment currently in use limits the number to six. One solution would be the use of a digitizer with a rapid and continuous mode point reader connected to a tape or disc data storage device. This would enable the operator to trace the image of a particle and produce a closer geometric approximation. The computer program could subsequently be modified to compute mass more accurately.

[5] J. N. Majerus, "A Model for Studying the Influence of Guidance Packages Upon Shaped Charge Warhead Performance," [illegible] (1976). (AD#B015299L).

APPENDIX A

PROCEDURES FOR PREPARING AND READING RADIOGRAPHS

The standard BRL flash radiographic test site contains holders for film cassettes, each cassette containing either three or four films. As a rule the films bear the flash number and the film number.

After developing the films, they are arranged according to their positions in the cassettes. The jet particles are then numbered starting with the jet tip and working back, with each particle having the same designated number for every flash.

Once the particles are identified, a set of six points, outlining a pair of trapezoids, is obtained for each particle. When measurements are taken of these points, the configuration will be interpreted as a pair of truncated cones in order to calculate mass. Figure A-1 describes the preparation of the jet particle images.

The film reading machine that is presently used for this procedure is the Data Reducer 099, manufactured by the Telecomputing Corp. Signals are sent from the 099 to a digitizer, developed for BRL by Mr. Donald F. Merritt. The digitizer then transmitts this information, in the form of data units per inch, to a MAI Equipment Corp. 523 Gang Summary Unit which punches the data onto computer cards.

The following procedures will enable the user to operate the film reading equipment:

1. Insert the wired circuit board labled "JET", label down, into the connection frame of the Gang Summary Unit.

2. Load the Gang Summary Unit feeder with blank computer cards.

3. Turn all three machines on, in any order.

4. Beginning with the first flash, place the film containing the jet tip onto the lighted reading surface of the 099. Arrange the film so that the jet is aligned horizontally on the lighted surface. The horizontal fiducial should run parallel to a line marked across the lighted surface as indicated in Figure 2. This is the x-direction. The vertical fiducial will indicate the y - direction.

5. By adjusting the large wheels located on either side of the console, place the cursor cross-hairs on the intersection of the x and y fiducials and press the button marked "ϕ" on the right of the console. This will assign (0,0) to the x/y intersection.

6. Located at the bottom-center of the digitizer console is a set of twelve registers with star-wheel adjustments. Reading from left to right, enter the round number in the first five registers, film number in the seventh and flash number in the eleventh.

7. The frame count windows in the center of the digitizer console should read zero in all units. If not, press the reset buttons until all units are zeroed.

8. Position the other switches and registers on the digitizer console as indicated in Table A-1.

9. With the cursor at (0,0), press the foot switch repeatedly until the number "1" appears in the frame count window. This will zero-out the memory in the card punch machine.

10. To read a particle place the cursor on each point, beginning with p_1 (Figure A-1), and press the foot switch for reading at each point. Repeat this step for every particle on the film.

Table A-1. Positions of Switches and Other Adjustments on the Electronic Digitizer

SWITCH	POSITION
Multiplier (x and y)	4
Direction (x)	Down
Direction (y)	Down
Normal/Test (x)	Normal
Normal/Test (y)	Normal
Printer (paper tape)	User's choice
Punch	on
Skip/Print Constants	Print (on)
Frame Count Advance	6

11. Repeat steps 4 through 10 for each film.

12. Change registers seven, film number, and eleven, flash number, when the film is changed.

13. After the particles are read for all flashes, sort the cards out by "reading the holes" in columns 77 through 80, and remove only the card for each particle that has punched holes for a "+" character over column 76. This will be the sixth (last) card for the particle.

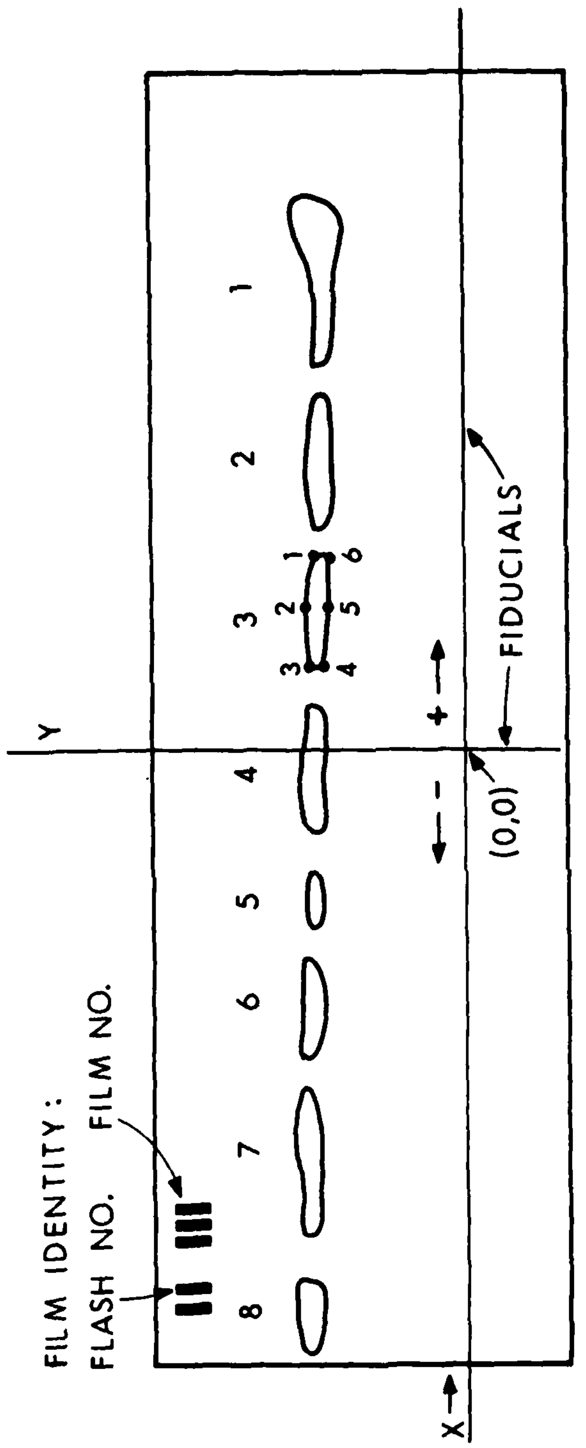

Figure A-1. Typical Radiograph of a Shaped-Charge Jet Mounted on Film Reading Device and Showing the Sequence for Reading a Particle

APPENDIX B

INPUT TO THE PROGRAM

Card 1:

Columns 1-5: ICASES - Number of rounds to be run.

6-10: LCL - Option for printing out the shaped-charge liner density. Enter 1 if print out is not desired. Otherwise, leave blank.

Card 2: Case Identifier and some constants.

Columns	1-5:	NROUND - Round Number
	6-10:	NPART - Number of jet particles
	11-15:	NFLASH - Number of flashes
	16-20	RHO - Shaped-charge liner density
	21-30:	XMAG1 - Magnification factor for first flash
	31-40:	XMAG2 - Magnification factor for second flash
	41-50:	XMAG3 - Magnification factor for third flash
	51-60:	Flash 1 - Delay time for first flash
	61-70:	Flash 2 - Delay time for second flash
	71-80:	Flash 3 - Delay time for third flash.

Card 3: More constants.

Columns 1-10: FOCUS 1 - Distance from the shaped-charge liner base to the focal level of the first x-ray tube.

11-20: FOCUS 2 - Distance from the shaped-charge liner base to the focal level of the second x-ray tube.

21-30: FOCUS 3 - Distance from the shaped-charge liner base to the focal level of the third x-ray tube.

31-40: F1A
41-50: F2A
51-60: F3A
61-70 F4A

Distances of film "y" fiducials to the focal level of Flash A. Digit is film number and letter (A, B or C) is flash. This also applies for Card 4 constants.

Card 4: More constants for fiducial measurements.

Columns	1-10:	F1B
	11-20:	F2B
	21-30:	F3B
	31-40:	F4B
	41-50:	F1C
	51-60:	F2C
	61-70:	F3C
	71-80:	F4C

Card 5: First particle card. All particle cards are identical in format. x and y coordinates are data units/inch in integer form.

Columns	1-5:	IX(1) - x coordinate of p_1
	6-10:	IY(1) - y coordinate of p_1
	11-15:	IX(2) - x coordinate of p_2
	16-20:	IY(2) - y coordinate of p_2
	21-25:	IX(3) - x coordinate of p_3
	26-30:	IY(3) - y coordinate of p_3
	31-35:	IX(4) - x coordinate of p_4
	36-40:	IY(4) - y coordinate of p_4
	41-45:	IX(5) - x coordinate of p_5
	46-50:	IY(5) - y coordinate of p_5
	51-55:	IX(6) - x coordinate of p_6
	56-60:	IY(6) - y coordinate of p_6
	65:	L - Flash number (1,2 or 3)
	70:	IFILM - Film number
	71-75:	IROUND - Round number
	77-80:	IPART - Particle number

APPENDIX C

PROGRAM LISTING

The program is written in FORTRAN IV and is currently on file in the BRL Control Data Corporation's CYBER 170/7600 system.

```
      PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)                 MAIN       2
      DIMENSION S1(100),S2(100),S3(100),VOL(100),XL(100),DIA(100),        MAIN       3
     1V1(100),V2(100),V3(100),VEL(100),XMASS(100),XKE(100),SUMKE(100),    MAIN       4
     2FLOC(100),XXL(100),SUML(100),IX(6),IY(6),ZX(6),ZY(6),               MAIN       5
     3HPEAK(100),SUMMAS(100),B(10000),DA(3),DB(3),XMAG(3)                 MAIN       6
      DIMENSION AA(2,3),CC(2),RR(500),AF(500),SIG(2),TT(2)                COPRA      1
      DIMENSION SA(10),SB(10),SC(10),SD(10),SE(10),SF(10),SL1(10),        MAIN       7
     1SL2(10),SL3(10),ST(10),L1(100),L2(100),L3(100)                      MAIN       8
      DIMENSION P(100),TOTP(100),SUMDIA(100),SUMLEN(100),XDIA(100),DELV(  MAIN       9
     1100),SDELV(100),SUMDEL(100)                                         MAIN      10
      DIMENSION XVOL(3,100)                                               MAIN      11
      DIMENSION AZ(100,100)                                               COPRR      1
      DATA SA(1),SA(2),SA(3)/10HVELOCITY (,10HMM/MICROSE,3HC)>/           MAIN      12
      DATA SB(1),SB(2),SB(3)/10HCUMULATIVE,10H MASS (GRA,4HMS)>/          MAIN      13
      DATA SC(1),SC(2),SC(3),SC(4)/10HPOSITION A,10HLONG JET L,10HENGTH   MAIN      14
     1(MM),1H>/                                                           MAIN      15
      DATA SD(1),SD(2),SD(3)/10HCUMULATIVE,10H K.E. (JOU,5HLES)>/         MAIN      16
      DATA SE(1),SE(2),SE(3),SE(4)/10HDISTANCE F,10HROM CHARGE,10H BASE   MAIN      17
     1(MM),1H>/                                                           MAIN      18
      DATA SF(1),SF(2),SF(3)/10HBREAK-UP T,10HIME (MICRO,5HSEC)>/         MAIN      19
      DATA SL1(1)/8HFLASH 1>/                                             MAIN      20
      DATA SL2(1)/8HFLASH 2>/                                             MAIN      21
      DATA SL3(1)/8HFLASH 3>/                                             MAIN      22
    1 FORMAT(3I5,F5.2,6F10.5)                                             MAIN      23
    2 FORMAT(7F10.5)                                                      MAIN      24
    6 FORMAT(8F10.5)                                                      MAIN      25
   21 FORMAT(2I5)                                                         MAIN      26
   30 FORMAT(12I5,2X,I1,2X,3I5)                                           MAIN      27
      READ(5,21) ICASES,LCL                                               MAIN      28
      IF(EOF(5)) 23,23                                                    MAIN      29
   23 DO 500 IJ=1,ICASES                                                  MAIN      30
   22 READ(5,1)NROUND,NPART,NFLASH,RHO,(XMAG(I),I=1,3),FLASH1,FLASH2,     MAIN      31
     1FLASH3                                                              MAIN      32
      IF(EOF(5)) 24,24                                                    MAIN      33
   24 ENCODE(21,20,ST(1)) NROUND                                          MAIN      34
   20 FORMAT(10HROUND NUMB,4HER  ,I5,2H >)                                MAIN      35
      READ(5,2) FOCUS1,FOCUS2,FOCUS3,F1A,F2A,F3A,F4A                      MAIN      36
      IF(EOF(5)) 25,25                                                    MAIN      37
   25 READ(5,6) F1B,F2B,F3B,F4B,F1C,F2C,F3C,F4C                           MAIN      38
      IF(EOF(5)) 26,26                                                    MAIN      39
   26 RO=RHO                                                              MAIN      40
      IF(LCL.NE.1) GO TO 29                                               MAIN      41
      RHO=0.                                                              MAIN      42
C                                                                         MAIN      43
C     ROUND INFORMATION CARD NEXT                                         MAIN      44
   29 PRINT 5                                                             MAIN      45
      PRINT 3, NROUND,RHO,(XMAG(N),N=1,3),FOCUS1,FOCUS2,FOCUS3,FLASH1,FL  MAIN      46
     1ASH2,FLASH3                                                         MAIN      47
    3 FORMAT(/////,20X,'ROUND NUMBER  ',I5,//,20X,'LINEP DENSITY(GM/CC)=  MAIN      48
     1 ',F6.1,/,20X,'MAGNIFICATION FACTOR=',3F9.5,/,20X,'DISTANCE FROM L  MAIN      49
     2INER BASE TO FOCAL POINT(MM)',/,25X,'FLASH 1= ',F6.1,/,25X,'FLASH   MAIN      50
     32= ',F6.1,/,25X,'FLASH 3= ',F6.1,/,20X,'DELAY TIMES (MICROSEC)',/,  MAIN      51
     425X,'FLASH 1= ',F6.1,/,25X,'FLASH 2= ',F6.1,/,25X,'FLASH 3= ',F6.1  MAIN      52
     5)                                                                   MAIN      53
      RHO=RO                                                              MAIN      54
      PRINT 5                                                             MAIN      55
    5 FORMAT(1H1)                                                         MAIN      56
```

```
      PRINT 4                                                           MAIN      57
    4 FORMAT(21X,'PARTICLE   AVG. VELOCITY   TOTAL JET     BREAK-UP',/,2 CORRA     2
     12X,'NUMBER',4X,'(MM/MICROSEC)',3X,'LENGTH(MM)',3X,'(MICROSEC)',/) CORRA     3
      PI=3.14159                                                        MAIN      60
      DO 150 I=1,NFLASH                                                 MAIN      61
      DO 149 J=1,NPART                                                  MAIN      62
      READ(5,30)(IX(K),IY(K),K=1,6),L,IFILM,IROUND,IPART                MAIN      63
      IF(EOF(5)) 32,32                                                  MAIN      64
   32 DO 35 M=1,6                                                       MAIN      65
      ZX(M)=FLOAT(IX(M))/15.5906                                        MAIN      66
   35 ZY(M)=FLOAT(IY(M))/15.5906                                        MAIN      67
      IF(ZX(1).EQ.ZX(2)) GO TO 40                                       MAIN      68
      R1=.5*SQRT((ZX(1)-ZX(6))**2+(ZY(1)-ZY(6))**2)*XMAG(I)             MAIN      69
      R2=.5*SQRT((ZX(2)-ZX(5))**2+(ZY(2)-ZY(5))**2)*XMAG(I)             MAIN      70
      R3=.5*SQRT((ZX(3)-ZX(4))**2+(ZY(3)-ZY(4))**2)*XMAG(I)             MAIN      71
      P1X=(ZX(1)+ZX(6))/2.                                              MAIN      72
      P1Y=(ZY(1)+ZY(6))/2.                                              MAIN      73
      P2X=(ZX(3)+ZX(4))/2.                                              MAIN      74
      P2Y=(ZY(3)+ZY(4))/2.                                              MAIN      75
      P3X=(ZX(2)+ZX(5))/2.                                              MAIN      76
      AZ(I,J)=(ZY(2)+ZY(5))/2.                                          CORRB     2
      P3Y=(ZY(2)+ZY(5))/2.                                              MAIN      77
      XH1=SQRT((P1X-P3X)**2+(P1Y-P3Y)**2)*XMAG(I)                       MAIN      78
      XH2=SQRT((P3X-P2X)**2+(P3Y-P2Y)**2)*XMAG(I)                       MAIN      79
      P1Z=P1X                                                           MAIN      80
      P1X=P2X                                                           MAIN      81
      GOTO 45                                                           MAIN      82
   40 P1X=ZX(1)                                                         MAIN      83
   45 IF(L.EQ.2) GOTO 55                                                MAIN      84
      IF(L.EQ.3) GOTO 65                                                MAIN      85
      IF(IFILM.EQ.2) GO TO 47                                           MAIN      86
      IF(IFILM.EQ.3) GO TO 48                                           MAIN      87
      IF(IFILM.EQ.4) GO TO 49                                           MAIN      88
      S1(J)=FOCUS1-(F1A-P1X)*XMAG(I)                                    MAIN      89
      GO TO 15                                                          MAIN      90
   47 S1(J)=FOCUS1-(F2A-P1X)*XMAG(I)                                    MAIN      91
      GO TO 15                                                          MAIN      92
   48 S1(J)=FOCUS1+(F3A+P1X)*XMAG(I)                                    MAIN      93
      GO TO 15                                                          MAIN      94
   49 S1(J)=FOCUS1+(F4A+P1X)*XMAG(I)                                    MAIN      95
   15 IF(ZX(1).EQ.ZX(2)) GO TO 50                                       MAIN      96
      L1(J)=0                                                           MAIN      97
      GOTO 75                                                           MAIN      98
   50 L1(J)=1                                                           MAIN      99
      GOTO 80                                                           MAIN     100
   55 IF(IFILM.EQ.2) GO TO 57                                           MAIN     101
      IF(IFILM.EQ.3) GO TO 58                                           MAIN     102
      IF(IFILM.EQ.4) GO TO 59                                           MAIN     103
      S2(J)=FOCUS2-(F1B-P1X)*XMAG(I)                                    MAIN     104
      GO TO 16                                                          MAIN     105
   57 S2(J)=FOCUS2-(F2B-P1X)*XMAG(I)                                    MAIN     106
      GO TO 16                                                          MAIN     107
   58 S2(J)=FOCUS2+(F3B+P1X)*XMAG(I)                                    MAIN     108
      GO TO 16                                                          MAIN     109
   59 S2(J)=FOCUS2+(F4B+P1X)*XMAG(I)                                    MAIN     110
   16 V1(J)=(S2(J)-S1(J))/(FLASH2-FLASH1)                               MAIN     111
      IF(ZX(1).EQ.ZX(2)) GO TO 60                                       MAIN     112
```

```
      L2(J)=0
      GOTO 75
   60 L2(J)=1
      GOTO 80
   65 IF(NFLASH.EQ.2) GOTO 80
      IF(IFILM.EQ.2) GO TO 67
      IF(IFILM.EQ.3) GO TO 68
      IF(IFILM.EQ.4) GO TO 69
      S3(J)=FOCUS3-(F1C-P1X)*XMAG(I)
      GO TO 17
   67 S3(J)=FOCUS3-(F2C-P1X)*XMAG(I)
      GO TO 17
   68 S3(J)=FOCUS3+(F3C+P1X)*XMAG(I)
      GO TO 17
   69 S3(J)=FOCUS3+(F4C+P1X)*XMAG(I)
   17 V2(J)=(S3(J)-S2(J))/(FLASH3-FLASH2)
      V3(J)=(S3(J)-S1(J))/(FLASH3-FLASH1)
      IF(ZX(1).EQ.ZX(2)) GO TO 70
      L3(J)=0
      GOTO 75
   70 L3(J)=1
      GOTO 80
   75 VOL(J)= VOL(J)+(PI*XH1/3.*(R1**2+R1*R2+R2**2)+PI*XH2/3.*(R2**2+R2*
     1R3+R3**2))
      P1X=P1Z
      XVOL(I,J)= PI*XH1/3.*(R1**2+R1*R2+R2**2)+PI*XH2/3.*(R2**2+R2*R3+
     1R3**2)
      XVOL(I,J)= XVOL(I,J)*.001*RHO
      XL(J)=XL(J)+SQRT((P1X-P2X)**2+(P1Y-P2Y)**2)*XMAG(I)
      DIA(J)=DIA(J)+2.*R2
   80 CONTINUE
      IF(I.LT.NFLASH) GOTO 149
      IF(NFLASH.EQ.2) GOTO 85
      IF(L1(J).EQ.1.AND.L2(J).EQ.1.AND.L3(J).EQ.1) GO TO 149
      IF(L1(J).EQ.0.AND.L2(J).EQ.0.AND.L3(J).EQ.0) GO TO 90
      IF(L2(J).EQ.1.AND.L3(J).EQ.1) GO TO 95
      IF(L1(J).EQ.1.AND.L3(J).EQ.1) GO TO 95
      IF(L1(J).EQ.1.AND.L2(J).EQ.1) GO TO 95
      IF(L2(J).EQ.0.AND.L3(J).EQ.0) GO TO 100
      IF(L1(J).EQ.0.AND.L3(J).EQ.0) GO TO 100
      IF(L1(J).EQ.0.AND.L2(J).EQ.0) GO TO 100
   85 IF(L1(J).EQ.1.AND.L2(J).EQ.1) GO TO 149
      IF(L1(J).EQ.0.AND.L2(J).EQ.0) GO TO 100
      IF(L1(J).EQ.0.OR.L2(J).EQ.0) GO TO 95
   90 XMASS(J)=VOL(J)*.001/3.*RHO
      XL(J)=XL(J)/3.
      DIA(J)=DIA(J)/3.
      GOTO 149
   95 XMASS(J)=VOL(J)*.001*RHO
      GOTO 149
  100 XMASS(J)=VOL(J)*.001/2.*RHO
      XL(J)=XL(J)/2.
      DIA(J)=DIA(J)/2.
  149 CONTINUE
  150 CONTINUE
      DO 170 N=1,NPART
      IF(NFLASH.EQ.2)GOTO 155
```

```
      VEL(N)=(V1(N)+V2(N)+V3(N))/3.*.1                                  MAIN     170
      GOTO 160                                                          MAIN     171
  155 VEL(N)=V1(N)*.1                                                   MAIN     172
  160 SUML(N)=XL(N)+SUML(N-1)                                           MAIN     173
      SUMMAS(N)=XMASS(N)+SUMMAS(N-1)                                    MAIN     174
      ELOD(N)=XL(N)/DIA(N)                                              MAIN     175
      VEL(N)=VEL(N)*10.                                                 MAIN     176
      XKE(N)=.5*XMASS(N)*.001*(VEL(N)*1000.)**2                         MAIN     177
      SUMKE(N)=XKE(N)+SUMKE(N-1)                                        MAIN     178
      P(N)=VEL(N)*XMASS(N)                                              MAIN     179
      TOTP(N)=P(N)+TOTP(N-1)                                            MAIN     180
      SUMDIA(N)=SUMDIA(N-1)+DIA(N)                                      MAIN     181
      IF(N.EQ.1)GOTO 165                                                MAIN     182
      BREAK(N)=SUML(N)/(VEL(1)-VEL(N))                                  MAIN     183
      GOTO 170                                                          MAIN     184
  165 BREAK(1)=0.0                                                      MAIN     185
  170 PRINT 171, N,VEL(N),SUML(N),BREAK(N)                              MAIN     186
  171 FORMAT(23X,I2,10X,F6.3,9X,F6.2,7X,F6.1)                           CORRA      4
      PRINT 52                                                          MAIN     188
   52 FORMAT(1H1,20X,'PARTICLE',4X,'VELOCITY1',6X,'VELOCITY2',6X,       CORRA      5
     1'VELOCITY3',/,22X,'NUMBER',3X,'(MM/MICROSEC)',2X,'(MM/MICROSEC)', CORRA      6
     22X,'(MM/MICROSEC)',/)                                             CORRA      7
      DO 172 J=1,NPART                                                  MAIN     190
  172 PRINT 173, J,V1(J),V2(J),V3(J)                                    MAIN     191
  173 FORMAT(23X,I2,9X,F6.3,9X,F6.3,9X,F6.3)                            CORRA      8
      PRINT 175                                                         MAIN     193
  175 FORMAT(1H1,20X,'PARTICLE   LENGTH    DIA.    L/D    MASS     TOTAL J MAIN     194
     1ET',/,22X,'NUMBER',5X,'(MM)',4X,'(MM)',9X,'(GRAMS)',2X,'MASS(GRAMS CORRA      9
     2)',/)                                                             CORRA     10
      DO 176 I=1,NPART                                                  MAIN     197
  176 PRINT 177, I,XL(I),DIA(I),ELOD(I),AMASS(I),SUMMAS(I)              MAIN     198
  177 FORMAT(23X,I2,8X,F4.1,4X,F4.1,2X,F4.1,4X,F5.2,5X,F6.2)            CORRA     11
      PRINT 603                                                         MAIN     200
  603 FORMAT(1H1,20X,'PARTICLE',4X,'MASS1',9X,'MASS2',9X,'MASS3',/,22X, CORRA     12
     1'NUMBER',4X,'(GRAMS)',7X,'(GRAMS)',7X,'(GRAMS)',/)                CORRA     13
      DO 600 J=1,NPART                                                  MAIN     202
      I=1                                                               CORRA     14
  600 WRITE(6,602) (J,XVOL(I,J),XVOL(I+1,J),XVOL(I+2,J))                CORRA     15
  602 FORMAT(23X,I2,6X,F8.4,6X,F8.4,6X,F8.4)                            CORRA     16
      PRINT 180                                                         MAIN     206
  180 FORMAT(1H1,20X,'PARTICLE     K.E.      TOTAL JET   DISTANCE FROM CH MAIN     207
     1ARGE BASE',/,22X,'NUMBER',4X,'(JOULES)',3X,'KE(JOULES)',2X,'FLASH CORRA     17
     21',2X,'FLASH 2',2X,'FLASH 3',/)                                   CORRA     18
      DO 181 I=1,NPART                                                  MAIN     210
  181 PRINT 182, I,XKE(I),SUMKE(I),S1(I),S2(I),S3(I)                    MAIN     211
  182 FORMAT(23X,I2,7X,F8.0,4X,F8.0,4X,F5.0,4X,F5.0,4X,F5.0)            CORRA     19
      PRINT 183                                                         MAIN     213
  183 FORMAT(1H1,20X,'PARTICLE',4X,'MOMENTUM',4X,'TOTAL JET',/,22X,'NUMB CORRA     20
     1ER',4X,'(KG-M/SEC)',3X,'MOMENTUM',/)                              CORRA     21
      DO 185 I=1,NPART                                                  MAIN     216
  185 PRINT 184,I,P(I),TOTP(I)                                          MAIN     217
  184 FORMAT(23X,I2,9X,F6.2,7X,F6.2)                                    CORRA     22
      PRINT 33                                                          CORRB      3
   33 FORMAT(1H1,21X,'PARTICLE',8X,'DEVIANCE FROM PATH (MM)',/,23X,     CORRB      4
     1'NUMBER',6X,'FLASH 1    FLASH 2    FLASH 3',/)                    CORRB      5
      DO 800 JJJ=1,NPART                                                CORRE      6
      WRITE (6,36) JJJ,AZ(1,JJJ),AZ(2,JJJ),AZ(3,JJJ)                    CORRE      7
```

```
   36 FORMAT(24X,I2,8X,F8.3,3X,F8.3,3X,F8.3)                                  CORRB       8
  400 CONTINUE                                                                CORRB       9
      DO 192 N=2,NPART                                                        MAIN      219
      SUMLEN(N)=SUMLEN(N-1)+XL(N)                                             MAIN      220
      XDIA(N)=XDIA(N-1)+DIA(N)                                                MAIN      221
      IF(N.EQ.2) GO TO 191                                                    MAIN      222
      DELV(N)=VEL(N-1)-VEL(N)                                                 MAIN      223
      GO TO 192                                                               MAIN      224
  191 DELV(N)=VEL(1)-VEL(N)                                                   MAIN      225
  192 SDELV(N)=SDELV(N-1)+DELV(N)                                             MAIN      226
      DO 195 J=3,NPART                                                        MAIN      227
  195 SUMDEL(J)=DELV(J)+SUMDEL(J-1)                                           MAIN      228
      AVL1=SUML(NPART)/FLOAT(NPART)                                           MAIN      229
      AVL2=SUMLEN(NPART)/FLOAT(NPART-1)                                       MAIN      230
      AVD1=SUMDIA(NPART)/FLOAT(NPART)                                         MAIN      231
      AVD2=XDIA(NPART)/FLOAT(NPART-1)                                         MAIN      232
      ADELV1=SDELV(NPART)/FLOAT(NPART-1)                                      MAIN      233
      ADELV2=SUMDEL(NPART)/FLOAT(NPART-2)                                     MAIN      234
      PRINT 200, AVL1,AVL2,AVD1,AVD2,ADELV1,ADELV2                            MAIN      235
  200 FORMAT(1H1,/////,47X,'WITH JET TIP    W/O TIP',/,20X,'AVERAGE PART      MAIN      236
     1ICLE LENGTH',7X,F6.2,7X,F6.2,/,20X,'AVERAGE PARTICLE DIAMETER',6X,      MAIN      237
     2F5.2,8X,F5.2,/,20X,'AVERAGE CHANGE IN VELOCITY',6X,F4.2,9X,F4.2)        MAIN      238
      PRINT 505                                                               MAIN      239
      NRA=2                                                                   CORRA      23
      NN=1                                                                    CORRA      24
      IC=0                                                                    CORRA      25
      CALL POLYLS(VEL,S1,NPART,AA,NRA,NN,CC,RR,AF,ERMS,SIG,TT,DET,IC)         CORRA      26
      WRITE(6,41) CC(1)                                                       CORRA      27
   41 FORMAT(20X,' VIRTUAL ORIGIN FOR FLASH 1=',F12.6)                        CORRA      28
      CALL POLYLS(VEL,S2,NPART,AA,NRA,NN,CC,RR,AF,ERMS,SIG,TT,DET,IC)         CORRA      29
      WRITE(6,42) CC(1)                                                       CORRA      30
   42 FORMAT(20X,' VIRTUAL ORIGIN FOR FLASH 2=',F12.6)                        CORRA      31
      IF(L.LT.3) GO TO 515                                                    CORRA      32
      CALL POLYLS(VEL,S3,NPART,AA,NRA,NN,CC,RR,AF,ERMS,SIG,TT,DET,IC)         CORRA      33
      WRITE(6,43) CC(1)                                                       CORRA      34
   43 FORMAT(20X,' VIRTUAL ORIGIN FOR FLASH 3=',F12.6)                        CORRA      35
  515 CONTINUE                                                                CORRA      36
  505 FORMAT(1H1)                                                             MAIN      240
      DO 510 JN= 1,NPART                                                      MAIN      241
      VOL(JN)=0.                                                              MAIN      242
      XL(JN)=0.                                                               MAIN      243
  510 DIA(JN)=0.                                                              MAIN      244
  500 CONTINUE                                                                MAIN      245
      STOP                                                                    MAIN      246
      END                                                                     MAIN      247
```

APPENDIX D

ALPHABETICAL LISTING OF PROGRAM VARIABLE NAMES

ADELV1: Average change in velocity between particles.

ADELV2: Average change in velocity between particles, excluding the jet tip.

AVD1: Average diameter of all particles.

AVD2: Average diameter of particles, excluding the jet tip.

BREAK: Break-up time.

DELVA: Change in velocity between particles.

DIA: Diameter of a particle.

ELOD: Length-to-diameter ratio of a particle.

L1, L2, L3: Flags for flashes 1,2 and 3 used for determining the average length, diameter and mass of a particle.

P: Momentum of a particle.

P1X, P2X, P3X: Computed x coordinates of points between p_1 and p_6, p_3 and p_4, and p_2 and p_5, respectively.

P1Y, P2Y, P3Y: Computed y coordinates of points between p_1 and p_6, p_3 and p_4, and p_2 and p_5, respectively.

R1: Radius of the front end of a particle.

R2: Radius of the mid-section of a particle.

R3: Radius of the back end of a particle.

S1: Computed distance from the shaped-charge liner base to the back end of a particle for the first flash.

S2: Computed distance from the shaped-charge liner base to the back end of a particle for the second flash.

S3: Computed distance from the shaped-charge liner base to the back end of a particle for the third flash.

SDELV: Summation of the changes in velocities between particles, used in the calculation of average change in velocity.

SUMDEL: Summation of the changes in velocities between particles excluding the jet tip.

SUMDIA: Summation of the diameters of all particles, used to compute average diameter.

SUMKE: Summation of all particle kinetic energies.

SUML: Summation of the lengths of all particles.

SUMLEN: Summation of the lengths of particles excluding the jet tip.

SUMMAS: Summation of the masses of all particles.

TOTP: Summation of the momentums of all particles.

V1: Velocity computed between the first and second flashes.

V2: Velocity computed between the second and third flashes.

V3: Velocity computed between the first and third flashes.

VEL: Average velocity of V1, V2 and V3.

VOL: Summation of the volumes of a particle over all flashes.

XDIA: Summation of all particle diameters excluding the jet tip.

XH1: Height of the truncated cone on the front end of a particle.

XH2: Height of the truncated cone on the back end of a particle.

XKE: Kinetic energy of a particle.

XL: Length of a particle averaged over all flashes.

XMASS: Mass of a particle averaged over all flashes.

XVOL: Mass of a particle for a particular flash.

ZX: X coordinate converted from data units/inch to millimeters.

ZY: Y coordinates converted from data units/inch to millimeters.

APPENDIX E

OUTPUT FROM A SAMPLE RUN

```
ROUND NUMBER   2203

LINER DENSITY(GM/CC)-  8.9
MAGNIFICATION FACTOR-   .92000   .92000   .92000
DISTANCE FROM LINER BASE TO FOCAL POINT(MM)
     FLASH 1-  914.4
     FLASH 2-  914.4
     FLASH 3-  914.4
DELAY TIMES (MICROSEC)
     FLASH 1-  161.9
     FLASH 2-  183.1
     FLASH 3-  202.9
```

PARTICLE NUMBER	AVG. VELOCITY (MM/MICROSEC)	TOTAL JET LENGTH(MM)	BREAK-UP (MICROSEC)
1	7.741	30.93	0.0
2	7.549	42.00	218.8
3	7.476	54.87	207.1
4	7.371	77.95	210.4
5	7.123	87.68	141.9
6	7.046	97.79	140.7
7	6.918	107.25	130.3
8	6.899	110.82	131.[illegible]
9	6.863	116.90	133.2
10	6.776	131.93	136.8
11	6.625	144.04	129.0
12	6.614	149.58	132.7
13	6.501	163.09	131.[illegible]
14	6.323	178.85	126.1
15	6.291	184.00	126.9
16	6.188	188.02	121.0
17	6.163	193.36	122.[illegible]
18	6.124	201.88	124.8
19	5.951	214.28	119.7
20	5.898	226.25	122.[illegible]
21	5.772	243.74	123.[illegible]
22	5.613	262.23	123.[illegible]
23	5.432	278.11	120.[illegible]
24	5.295	288.03	117.[illegible]
25	5.247	298.54	119.7
26	5.169	310.01	120.[illegible]
27	5.075	321.11	120.[illegible]
28	4.944	331.04	118.4
29	4.842	350.73	121.[illegible]
30	4.674	368.56	120.[illegible]
31	4.588	376.67	119.[illegible]
32	4.501	394.92	121.[illegible]
33	4.414	407.47	122.[illegible]
34	4.213	430.33	[illegible]
35	4.088	441.84	120.[illegible]
36	4.046	454.14	122.[illegible]
37	3.879	473.40	122.[illegible]
38	3.629	494.02	120.[illegible]
39	3.555	510.84	122.[illegible]
40	3.333	538.79	122.[illegible]
41	3.177	554.78	121.[illegible]
42	3.066	574.32	122.9
43	2.822	595.34	121.[illegible]

PARTICLE NUMBER	VELOCITY1 (MM/MICROSEC)	VELOCITY2 (MM/MICROSEC)	VELOCITY3 (MM/MICROSEC)
1	7.773	7.709	7.742
2	7.573	7.525	7.550
3	7.483	7.469	7.476
4	7.586	7.150	7.376
5	7.244	6.999	7.126
6	7.163	6.926	7.049
7	7.048	6.785	6.921
8	7.009	6.786	6.901
9	6.987	6.737	6.866
10	6.886	6.664	6.779
11	6.728	6.519	6.627
12	6.580	6.649	6.613
13	6.555	6.445	6.502
14	6.370	6.275	6.324
15	6.325	6.256	6.292
16	6.239	6.135	6.189
17	6.206	6.119	6.164
18	6.178	6.068	6.125
19	6.014	5.888	5.963
20	5.950	5.846	5.900
21	5.849	5.692	5.774
22	5.699	5.524	5.615
23	5.532	5.330	5.435
24	5.362	5.226	5.297
25	5.307	5.186	5.248
26	5.227	5.108	5.170
27	5.123	5.026	5.076
28	5.020	4.867	4.946
29	5.823	3.839	4.865
30	4.797	4.548	4.677
31	4.694	4.479	4.591
32	4.621	4.376	4.503
33	4.509	4.317	4.416
34	4.330	4.093	4.216
35	4.209	3.964	4.090
36	4.175	3.915	4.049
37	3.979	3.776	3.881
38	3.787	3.468	3.633
39	3.699	3.408	3.559
40	3.457	3.205	3.336
41	3.305	3.046	3.160
42	3.253	2.876	3.071
43	2.953	2.668	2.825

PARTICLE NUMBER	LENGTH (MM)	DIA. (MM)	L/D	MASS (GRAMS)	TOTAL JET MASS(GRAMS)
1	30.9	4.8	6.4	3.70	3.70
2	11.1	2.5	4.4	.29	3.99
3	12.9	2.9	4.5	.41	4.40
4	23.1	2.8	8.3	.73	5.14
5	9.7	2.9	3.4	.30	5.44
6	10.1	2.7	3.7	.31	5.75
7	9.5	2.3	4.1	.23	5.97
8	3.6	2.0	1.8	.07	6.04
9	6.1	2.4	2.6	.14	6.18
10	15.0	2.6	5.8	.48	6.66
11	12.1	2.4	5.0	.30	6.97
12	5.5	2.5	2.2	.15	7.12
13	13.5	2.9	4.7	.42	7.54
14	15.8	2.5	6.3	.43	7.97
15	5.1	2.2	2.3	.11	8.07
16	4.0	2.1	1.9	.07	8.14
17	5.3	2.5	2.1	.13	8.28
18	8.5	2.8	3.1	.25	8.52
19	12.4	2.8	4.4	.40	8.93
20	12.0	2.3	5.3	.27	9.19
21	17.5	2.3	7.7	.42	9.61
22	18.5	2.6	7.1	.50	10.10
23	15.9	2.6	6.0	.44	10.55
24	9.9	2.8	3.5	.31	10.86
25	10.5	2.7	3.9	.31	11.17
26	11.5	2.6	4.5	.31	11.48
27	11.1	3.0	3.7	.39	11.88
28	9.9	2.9	3.5	.32	12.20
29	19.7	2.9	6.9	.66	12.87
30	17.8	2.8	6.3	.55	13.42
31	8.1	2.9	2.8	.25	13.66
32	18.3	2.6	7.0	.51	14.17
33	12.5	3.1	4.0	.47	14.64
34	22.9	2.8	8.1	.73	15.37
35	11.5	2.9	4.0	.39	15.76
36	12.3	3.2	3.9	.46	16.22
37	19.3	3.0	6.4	.78	17.00
38	20.6	3.6	5.6	.96	17.96
39	16.8	3.0	5.6	.66	18.61
40	27.9	3.5	8.0	1.49	20.11
41	16.0	3.6	4.5	.73	20.84
42	19.5	4.0	4.9	1.10	21.94
43	21.0	3.9	5.3	1.24	23.18

PARTICLE NUMBER	MASS1 (GRAMS)	MASS2 (GRAMS)	MASS3 (GRAMS)
1	3.2790	3.7919	4.0380
2	.2431	.3145	.3044
3	.3305	.5462	.3644
4	.7037	0.0000	.7587
5	.2584	.3559	.2993
6	.2835	.3017	.3442
7	.1980	.2552	.2219
8	.0553	.0600	.0604
9	.1137	.1287	.1890
10	.4704	.4470	.5257
11	.2633	.3399	.3070
12	.1232	.1771	0.0000
13	.3949	.4784	.3792
14	.4385	.4003	.4510
15	.0947	.0979	.1233
16	.0725	.0615	.0746
17	.0923	.1691	.1431
18	.2072	.3005	.2321
19	.2944	.5067	.4109
20	.2320	.3066	.2623
21	.2949	.4622	.4694
22	.4570	.4864	.5437
23	.4447	.3612	.5205
24	.3100	.3123	.3067
25	.2668	.3094	.3429
26	.3022	.3063	.3340
27	.4153	.3907	.3757
28	.3499	.3318	.2924
29	.6938	0.0000	.6331
30	.6149	.5427	.4927
31	.3094	.1883	.2465
32	.7093	.3562	.4584
33	.4304	.5044	0.0000
34	.7279	.6439	.6306
35	.3945	.3630	.4038
36	.4736	.5001	.3942
37	.9466	.6912	.7134
38	1.2210	.9140	.7421
39	.5911	.4527	.9220
40	1.6889	1.5923	1.1957
41	.7484	.6758	.7803
42	1.2289	1.1217	.9560
43	1.3572	1.1849	1.1808

PARTICLE NUMBER	K.E. (JOULES)	TOTAL JET KE(JOULES)	DISTANCE FROM CHARGE BASE (MM) FLASH 1	FLASH 2	FLASH 3
1	110950.	110950.	1005.	1170.	1323.
2	8188.	119138.	980.	1140.	1289.
3	11561.	130699.	964.	1123.	1271.
4	19862.	150560.	930.	1091.	1233.
5	7726.	158286.	915.	1069.	1207.
6	7690.	165976.	902.	1054.	1191.
7	5384.	171360.	888.	1038.	1172.
8	1552.	172912.	884.	1032.	1167.
9	3387.	176299.	876.	1025.	1158.
10	11045.	187345.	859.	1005.	1137.
11	6657.	194002.	841.	983.	1112.
12	3285.	197286.	831.	970.	1102.
13	8821.	206108.	816.	955.	1083.
14	8594.	214702.	794.	929.	1063.
15	2083.	216785.	788.	922.	1046.
16	1331.	218117.	782.	914.	1036.
17	2560.	220677.	776.	907.	1028.
18	4624.	225300.	766.	897.	1017.
19	7154.	232455.	749.	876.	993.
20	4644.	237099.	736.	862.	978.
21	6924.	244023.	715.	839.	962.
22	7807.	251830.	689.	810.	920.
23	6524.	258354.	669.	786.	892.
24	4341.	262695.	655.	769.	872.
25	4309.	267004.	645.	757.	860.
26	4196.	271200.	633.	743.	845.
27	5073.	276273.	621.	729.	829.
28	3969.	280242.	608.	714.	811.
29	7777.	288020.	587.	710.	788.
30	6009.	294029.	566.	688.	758.
31	2611.	296640.	557.	657.	746.
32	5145.	301784.	538.	636.	723.
33	4554.	306338.	523.	619.	704.
34	6515.	312853.	500.	592.	673.
35	3234.	316087.	488.	577.	655.
36	3733.	319820.	475.	563.	641.
37	5895.	325715.	452.	537.	611.
38	6315.	332030.	425.	505.	574.
39	4141.	336172.	409.	487.	555.
40	8287.	344459.	381.	466.	518.
41	3709.	348167.	366.	436.	496.
42	5182.	353349.	345.	414.	471.
43	4942.	358292.	323.	388.	439.

PARTICLE NUMBER	MOMENTUM (KG-M/SEC)	TOTAL JET MOMENTUM
1	28.67	28.67
2	2.17	30.83
3	3.09	33.93
4	5.39	39.32
5	2.17	41.49
6	2.18	43.67
7	1.56	45.23
8	.45	45.68
9	.99	46.66
10	3.26	49.92
11	2.01	51.93
12	.99	52.92
13	2.71	55.64
14	2.72	58.36
15	.66	59.02
16	.43	59.45
17	.83	60.28
18	1.51	61.79
19	2.40	64.20
20	1.57	65.77
21	2.40	68.17
22	2.78	70.95
23	2.40	73.35
24	1.64	74.99
25	1.64	76.64
26	1.62	78.26
27	2.00	80.26
28	1.61	81.86
29	3.21	85.08
30	2.57	87.65
31	1.14	88.79
32	2.29	91.07
33	2.06	93.13
34	3.09	96.23
35	1.58	97.81
36	1.84	99.65
37	3.04	102.69
38	3.48	106.17
39	2.33	108.50
40	4.97	113.48
41	2.33	115.81
42	3.38	119.19
43	3.50	122.69

	WITH JET TIP	W/O TIP
AVERAGE PARTICLE LENGTH (mm)	13.85	13.44
AVERAGE PARTICLE DIAMETER (mm)	2.84	2.79
AVERAGE CHANGE IN VELOCITY (mm/μsec)	.12	.12

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VIRTUAL ORIGIN FOR FLASH 1=  -85.118956 MM
VIRTUAL ORIGIN FOR FLASH 2=  -81.133748 MM
VIRTUAL ORIGIN FOR FLASH 3=  -85.896955 MM
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